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REACTOR NEUTRINOS

Neutrino Oscillations at Reactors: What Is Next?*

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Abstract—We briefly review previous and future reactor experiments aimed at searches for neutrino masses and mixing. We also consider the new idea to seek small mixing-angle oscillations in the atmospheric-neutrino-mass-parameter region at Krasnoyarsk. © *2000 MAIK "Nauka/Interperiodica".*

1. INTRODUCTION

The first long-baseline reactor experiment CHOOZ'97 [1] successfully reached the atmospheric-neutrino-mass-parameter region $\delta m^2_{\rm atm} \sim 10^{-3}$ eV^2 and tested there a large portion of the area of interest in the δm^2–$\sin^2 2\theta$ plane. No evidence for oscillations has been found. Thus, oscillations of electron neutrinos cannot dominate in the atmospheric-neutrino anomaly.

The Super-Kamiokande data on atmospheric neutrinos provide strong evidence for intensive $\nu_\mu \longrightarrow \nu_x$ ($x \neq e$) transitions [2]. In the three-active-neutrino (ν_e, ν_μ, ν_τ) oscillation model considered here, we have $\nu_x = \nu_\tau$.

We wish to emphasize, however, that both experiments, CHOOZ'97 and SuperKamiokande, do not rule out $\nu_e \rightleftarrows \nu_\mu$ oscillations as a subdominant mode in the $\delta m^2_{\rm atm}$ region [3, 4].

The results of recent experiments have attracted much attention to the problem of neutrino oscillations. New physical ideas and projects of new large-scale experiments at accelerators are being vigorously discussed [4].

What new contributions can be made with reactor electron antineutrinos for exploring the problems of the electron-neutrino mass and mixing?

One line of future studies has already been announced. To probe the large-mixing-angle (LMA) MSW solution ($\delta m^2_{\rm sol} \simeq 10^{-4}$–$10^{-5}$ eV^2, $\sin^2 2\theta \sim 0.7$) [5] of the solar-neutrino puzzle, the projects KamLAND at Kamioka [6] and BOREXINO at Gran Sasso [7] plan to detect neutrinos from reactors operating hundred kilometers away from the detector sites.

In this article, we consider another possibility. We find that, with two-detector techniques, the sensitivity to the mixing parameter in the $\delta m^2_{\rm atm}$ region can be substantially increased in relation to that achieved in CHOOZ. We propose a new study of the problem at the Krasnoyarsk underground (600 mwe) laboratory with detectors situated 1100 and 250 m from the reactor. The main goals of the proposed experiment are (1) to obtain deeper insight into the role of the electron neutrino in the atmospheric neutrino anomaly, (2) to obtain new information about neutrino mixing (the U_{e3} element of the neutrino mixing matrix can be measured), and (3) to ensure normalization for future long-baseline experiments at accelerators.

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2. OSCILLATIONS OF REACTOR ANTINEUTRINOS

A nuclear reactor generates antineutrinos at a rate of $N_\nu \sim 1.8 \times 10^{20}$ s^{-1} per 1 GW of thermal power. A typical reactor-$\bar\nu_e$ energy spectrum normalized to one fission event is presented in Fig. 1.

These electron antineutrinos are detected via the inverse beta-decay reaction

$$\bar\nu_e + p \longrightarrow e^+ + n. \quad (1)$$

The positron kinetic energy T is related to the electron-antineutrino energy E as

$$T = E - 1.804 \text{ MeV}. \quad (1a)$$

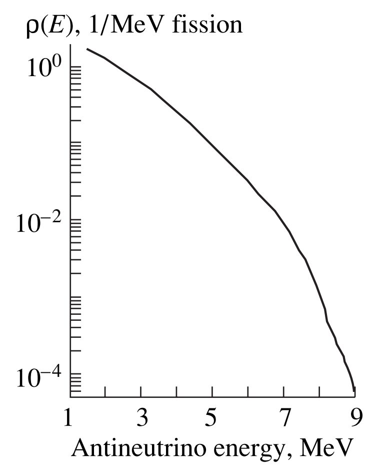

Fig. 1. Energy spectrum of reactor antineutrinos.

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The signature of electron-antineutrino absorption in a liquid-scintillator target is a spatially correlated delayed coincidence of the prompt positron and the signal from the neutron-capture gamma rays.

The probability $P(\bar{\nu}_e \longrightarrow \bar{\nu}_e)$ for $\bar{\nu}_e$ to survive at a distance R (m) from the source is given by the expression

$$P(\bar{\nu}_e \longrightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta \sin^2\left(1.27\delta m^2 \frac{R}{E}\right), \quad (2)$$

where E(MeV) is the neutrino energy, δm^2 is the mass parameter in eV^2, and $\sin^2 2\theta$ is the mixing parameter. The distortion of the positron energy spectrum and the deficit of the total electron-antineutrino-detection rate relative to the no-oscillation case are signatures for oscillations that are sought experimentally. The deficit of the total rate is the strongest for $(R\delta m^2)_{\max} \approx 5m$ eV^2.

In pressurized water reactors (PWR), the electron-antineutrino spectrum and the total cross section for reaction (1) vary with the nuclear-fuel composition, (the burnup effect). The current fuel composition is provided by reactor services. When the fuel composition is known, the no-oscillation cross section σ_{V-A} can be calculated within the uncertainty of 2.7%. (For more information see, for example, [8] and references therein.) With the aid of an integral-type detector, the CdF–KURCHATOV–LAPP group measured accurately the cross section at a distance of 15 m from the Bugey-5 reactor [9]:

$$\sigma_{\mathrm{expt}} = 5.750 \times 10^{-43}\ \mathrm{cm}^2/\mathrm{fission} \pm 1.4\%. \quad (3)$$

This highly accurate value σ_{expt} can be used in other experiments with reactor antineutrinos as a no-oscillation metrological reference. When it is used in practice, one must consider the differences in the fuel compositions and take into account the number of "small effects." This increases the error up to about 2%.

3. PAST, CURRENT, AND FUTURE EXPERIMENTS

Intensive searches for neutrino oscillations with detectors located at distances from reactors in the range between about 10 and 230 m were performed from 1980 to 1995. These "short-baseline" experiments are listed in Fig. 2 (left panel). The highest sensitivity to the mixing parameter ($\sin^2 2\theta \approx 0.02$) was achieved by the Bugey-3 group in the measurements with two identical detectors located at distances of 15 and 40 m from the reactor [9] (Fig. 3).

The CHOOZ detector used a 5-t liquid scintillator (Gd) target. It was located in an underground laboratory (300 mwe) at a distance of about 1 km from the neutrino source. The ratio R of the measured neutrino-detection rate to that expected in the no-oscillation case

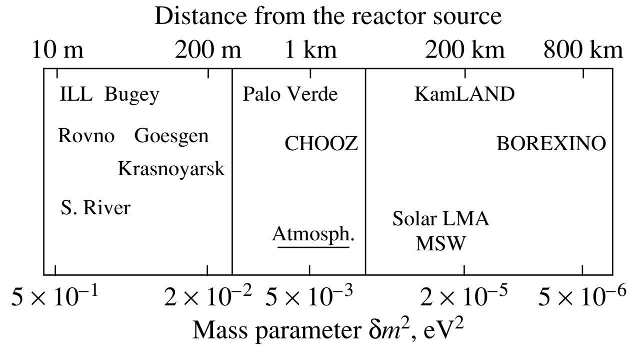

Fig. 2. Reactor oscillation experiments: (left panel) past short-baseline experiments, (middle panel) current long-baseline experiments, and (right panel) future ultralong-baseline experiments. New Krasnoyarsk project is not included.

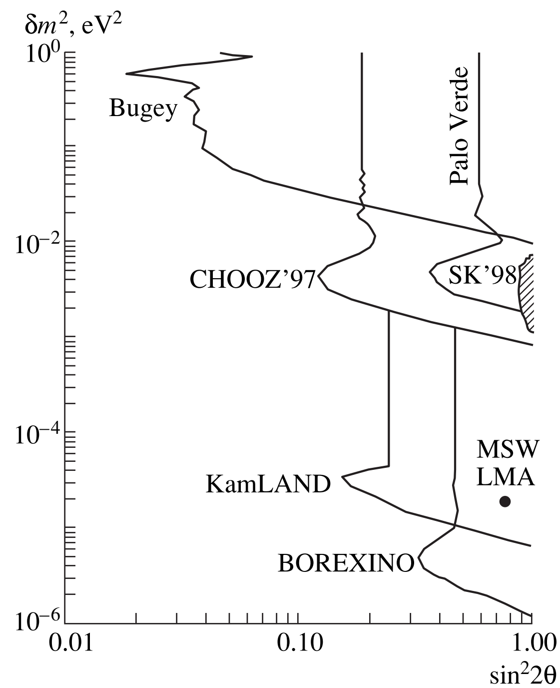

Fig. 3. Plots of reactor oscillation parameters. Bugey [10], CHOOZ'97 [1], and Palo Verde [11] are the 90% C.L. antineutrino-disappearance limits; KamLAND [6] and BOREXINO [7] are the expected $\bar{\nu}_e$ disappearance sensitivities; SK'98 [2] is the allowed $\nu_\mu \longrightarrow \nu_\tau$ oscillation region; and MSW LMA [5] is the solar ν_e solution.

was (November 1997)

$$R = 0.98 + 0.04(\mathrm{stat.}) + 0.04(\mathrm{syst.}). \quad (4)$$

The systematic errors come mainly from the reactor properties and the absolute values of neutrino-detection efficiencies. The 90% C.L. exclusion plot CHOOZ'97 for $\bar{\nu}_e$ disappearance channel is presented in Fig. 3, along with the allowed $\nu_\mu \longrightarrow \nu_\tau$ oscillation channel SK'736d [2] (shaded area). The experiment was contin-

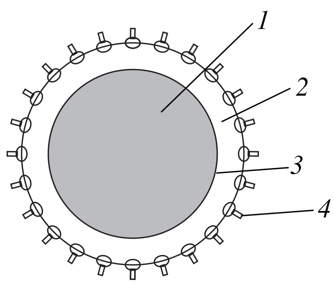

Fig. 4. Layout of the detector: (*1*) neutrino target (50 t of mineral oil + PPO), (*2*) mineral oil, (*3*) transparent film, and (*4*) photomultiplier tubes.

ued until June 1998 in order to achieve better statistics and to improve systematics. The final CHOOZ results will appear soon. The Palo Verde oscillation experiment deployed at a distance of 800 m from three reactors has been taking data since October 1998. The first 70-day results are now available [11]. Past and current experiments cover now the distances from the reactor of up to 1 km. The extension to about 200 and to about 800 km is expected from the forthcoming KamLAND and BOREXINO ultralong-baseline projects (Fig. 2). They will use liquid scintillator targets of 1000 and 300 t, respectively. The large-mixing-angle solar MSW solution [7] is well inside the area planned for the investigation (Fig. 3).

The experimental goal of the new search at Krasnoyarsk is to extend studies to the white-spot area left by the CHOOZ limits in Fig. 3.

4. NEW PROJECT FOR KRASNOYARSK

4.1 Detectors

Two identical liquid scintillation spectrometers positioned at the Krasnoyarsk underground site (600 mwe) at the distances of $R_1 = 1100$ m and $R_2 = 250$ m from the reactor source simultaneously detect (e^+, n) pairs produced in reaction (1). A simplified version of the BOREXINO detector composition is chosen for the design of the spectrometers (Fig. 4). Targets of weight 50 t each positioned at the center of the detectors (mineral oil + PPO) are viewed by photomultiplier tubes (~20% coverage, ~120 ph.e./MeV) through a nonscintillating-oil layer of thickness about 1 m. The computed neutrino detection rates can be seen in the middle of Table 1. For the sake of comparison, the parameters of the CHOOZ and the future KamLAND and BOREXINO detectors are also included.

4.2. Background

The CHOOZ experiment showed radical improvements of the reactor-neutrino techniques. A background level lower than that in previous reactor experiments by a factor of 500 to 1000 has been achieved (see the first three columns in Table 2). It is important to note that, with the CHOOZ experience and with the detailed studies at the BOREXINO CTF detector [7], the main features of the background suppression are now well understood, at least at the level we need. They are the following:

(1) In order to reduce the flux of cosmic muons—the main source of background in experiments of this type—a detector should be located underground at sufficiently large depth.

(2) In order to reduce the accidental background, the photomultipliers, with their highly radioactive glass, should be separated from the central scintillator volume by a sufficiently thick layer of oil (“BOREXINO geometry,” Fig. 4).

We estimate the total background rate as 0.1 per day per ton of the target. It is 2.5 times lower than the back-

Table 1. Antineutrino detection rates $N(e^+, n)\ d^{-1}$

Detector	CHOOZ’97	This project		KamLAND	BOREXINO
Mass of the target, t	5	50	50	1000	300
Distance from the source, km	1	0.25	1.1	~200	~800
$N(e^+, n)\ d^{-1}$	12	1000	55	2	0.08

Table 2. Neutrino signal $N(e^+, n)$ and background N_{BKG} rates (per day per ton of scintillator target)

Detector	Rovno	Bugey*	CHOOZ’97	This project**	KamLAND	BOREXINO
MWE***	30	~10	300	600	2700	3200
$N(e^+, n)$	1700	370	2.4	1.1	2×10^{-3}	3×10^{-4}
N_{BKG}	220	160	0.24	~0.1	<10	<10

* Detector at a distance of 40 m.
** Detector at a distance of 1100 m.
*** Overburden in meters of water equivalent.

ground measured at CHOOZ; this seems reasonable for a detector located twice as deep underground (Table 2).

4.3. Data Analysis

In three years of data taking, 40×10^3 (800×10^3) neutrino events with the signal-to-background ratio of 10 : 1 can be accumulated at a distance of 1100 m (250 m) from the reactor. Two types of analysis can be used. Neither is affected by the value of the absolute $\bar{\nu}_e$ flux and $\bar{\nu}_e$ energy spectrum, the reactor power, the burnup effects, and the absolute values of the detector efficiencies.

Analysis I is based on the ratio $X_{\rm rate} = N_1/N_2$ of the neutrino detection rates measured at two distances:

$$X_{\rm rate} = \frac{R_2^2 \epsilon_1 V_1}{R_1^2 \epsilon_2 V_2} F(\delta m^2, \sin^2 2\theta). \quad (5)$$

Here, $\epsilon_{1,2}$ and $V_{1,2}$ are the neutrino detection efficiencies and the scintillator volumes, respectively. Thus, the absolute values of the detection efficiencies are virtually canceled—only their small relative differences are to be considered here.

Analysis II is based on a comparison of the shapes of the positron spectra $S(E_e)$ measured simultaneously in two detectors. Small deviations of the ratio $X_{\rm shape} = S_1/S_2$,

$$X_{\rm shape} = C(1-\sin^2 2\theta \sin^2\phi_1)(1-\sin^2 2\theta \sin^2\phi_2)^{-1}, \quad (6)$$

from a constant value are sought as an indication of the oscillations ($\phi_{1,2}$ stands for $1.27\delta m^2 R_{1,2}E^{-1}$). No knowledge of the constant C in (6) is needed for this analysis, so that the details of geometry, the ratio of the target volumes, and the efficiencies are excluded from the consideration.

4.4. Detector Calibrations

Calibrations of the detectors are of crucial importance. The difference between the response functions for the two detectors, which is difficult to avoid, can produce some modulation of the ratio in (6), thereby mimicking the oscillation effect. The differences can be measured, and relevant corrections can be found. This can be done by a global comparison of the scales at many energy points by using the sources of gamma rays shown in Fig. 5.

An additional approach is also considered. The spectrometers can be tested periodically with the source that is provided by spontaneous fission of ^{252}Cf and which can produce a broad spectrum due to prompt gamma rays and neutron recoils (Fig. 5). The ratio of these spectra should be constant; if the instrumental modulation is observed, it can be measured and used to find corrections to (6).

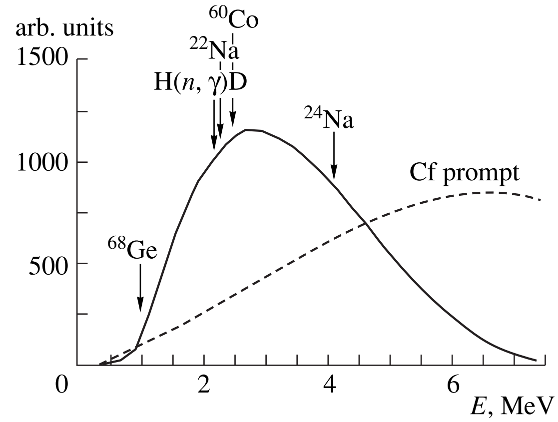

Fig. 5. Sources for detector calibrations. The solid line is the positron energy spectrum.

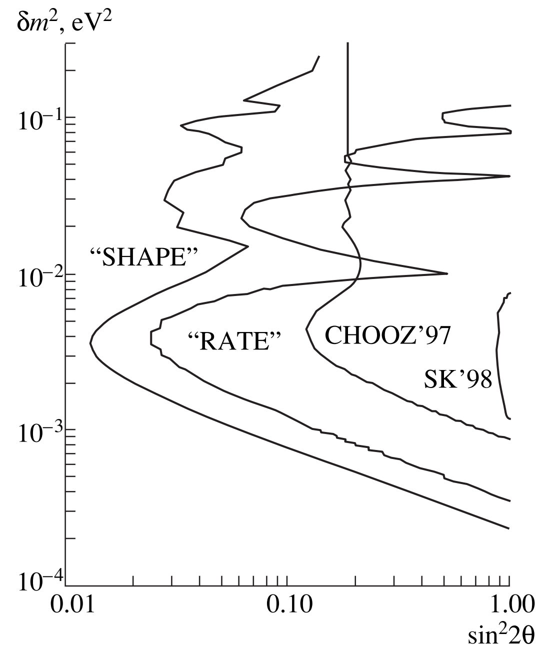

Fig. 6. Expected 90% C.L. oscillation-parameter limits: ("RATE") analysis I and ("SHAPE") analysis II.

4.5. Expected Constraints on the Oscillation Parameters

We hope that the ratio $\epsilon_1 V_1/\epsilon_2 V_2 \approx 1$ (5) can be controlled to within 0.8%. From Analysis I, we then expect the 90% C.L. limits shown in Fig. 6 (curve labeled "RATE"). We believe that the spurious effects in (6) can be controlled down to a level of 0.5%. The relevant 90% C.L. limits are presented in Fig. 6 (curve "SHAPE").

5. DISCUSSION AND CONCLUSIONS

By using the methods for data analysis that are mentioned in Section 4, we have obtained limits on the oscillation parameters free from the main sources of systematic uncertainties, which limit the sensitivity of experiments based on an absolute comparison of the measured and expected no-oscillation rates and positron spectra. Nevertheless, the systematic errors that remain reduce significantly the sensitivity to the mixing parameter $\sin^2 2\theta$. The curve "SHAPE" (Fig. 6) is about two times less restrictive in relation to the statistical limits found for an ideal detector with no systematic effects.

We return to the main question of what contributions to the neutrino physics can be expected from new oscillation experiments at reactors.

Long-baseline (LBL) experiments with detectors positioned at a distance of about 1 km from the reactor seek the mixing parameter $\sin^2 2\theta_{\rm LBL}$, which is expressed, in this case, as

$$\sin^2 2\theta_{\rm LBL} = 4U_{e3}^2(1 - U_{e3}^2), \quad (7)$$

where U_{e3}^2 is the contribution of the heaviest mass eigenstate ν_3 to the flavor electron neutrino state:

$$\nu_e = U_{e1}\nu_1 + U_{e2}\nu_2 + U_{e3}\nu_3. \quad (8)$$

From CHOOZ'97 results, we already know that U_{e3}^2 is not large: $U_{e3}^2 < (3–5) \times 10^{-2}$. The future 1-km experiment considered here can measure U_{e3}^2 or set a much smaller upper limit. Therefore, a better understanding of the neutrino mixing can be achieved. New information about U_{e3} can be useful for an analysis of atmospheric neutrinos and can give hints for future long-baseline experiments at accelerators.

The ultralong-baseline (ULBL) experiments KamLAND and BOREXINO will seek $\sin^2 2\theta_{\rm ULBL}$, which depends on the contributions of the ν_1 and ν_2 mass states:

$$\sin^2 2\theta_{\rm ULBL} = 4U_{e1}^2 U_{e2}^2. \quad (9)$$

We conclude that the experiments at reactors discussed here can provide full information about the mass structure of the electron neutrino, at least in the three-neutrino oscillation model.

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